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# COMPUTED ENVELOPE LINEARITY OF SEVERAL FM BROADCAST ANTENNA ARRAYS

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## COMPUTED ENVELOPE LINEARITY OF SEVERAL FM BROADCAST ANTENNA ARRAYS

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**Abstract:** This paper reports on calculations made to determine the envelope linearity of several FM broadcast antennas, a parameter of interest in digital broadcasting, such as HD Radio™. These computations assumed free space radiation and a simplified model of the radiating structure. A commercially available wire antenna analysis program was used for all antenna impedance and radiation calculations. Off-line processing was used for data analysis and extraction of gain and delay behavior across the broadcast channel. Results show that in most cases studied the antenna system causes only a small degradation to the modulation complex envelope. The performance is shown to vary, however, depending on the equivalent source impedance of the transmitter.

**Introduction:** For many communications channels it is desirable to have a broadband frequency response. Specifically, over sufficient bandwidth the amplitude response should be constant and the phase response should be linear, that is, the delay should be constant. Such a channel will maintain the complex envelope of transmissions undistorted.

This requirement has long been appreciated for analog FM broadcasting. It is particularly important for high quality stereo FM performance. With the introduction of HD Radio™ and its wider bandwidth, questions necessarily arise as to the suitability of existing antenna systems for this service. This paper presents calculated data to show the degree to which a typical antenna might degrade the channel envelope linearity.

The iBiquity Digital Corporation HD Radio™ specification for gain and delay flatness is<sup>1</sup>:

“The total gain of the transmission signal path as verified at the antenna output shall be flat to within +/- 0.5 dB for all frequencies between ( $F_c - 200$  kHz) to ( $F_c + 200$  kHz), where  $F_c$  is the RF channel frequency.”

“ The differential group delay variation of the entire transmission signal path (excluding the RF channel) as measured at the RF channel frequency ( $F_c$ ) shall be within 600 ns peak to peak from ( $F_c - 200$  kHz) to ( $F_c + 200$  kHz).”

It is against this specification that the data presented below are considered.

**System Analysis:** Figure 1 shows the linear system to be analyzed. An antenna or antenna array radiates into free space. The array is fed by a transmitter modeled as a Norton equivalent circuit through ideal lossless transmission line (typically some hundreds of feet in length), then through some feed system consisting typically of power dividers and shorter rf cables. The radiated electric far field is computed (at a distance of infinity) in a non-reflective environment. Complex-valued data for the theta and phi components of the field are generated and combined through a Hermitian dot product to give the right hand circular polarization (rhcp) component of the

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<sup>1</sup> Doc. No. SY\_SSS\_1026s, Rev D, February 18, 2005, “HD Radio FM Transmission System Specifications”

radiation. This was done to eliminate the need to study the horizontal and vertical polarization components separately, as they were seen to behave similarly.

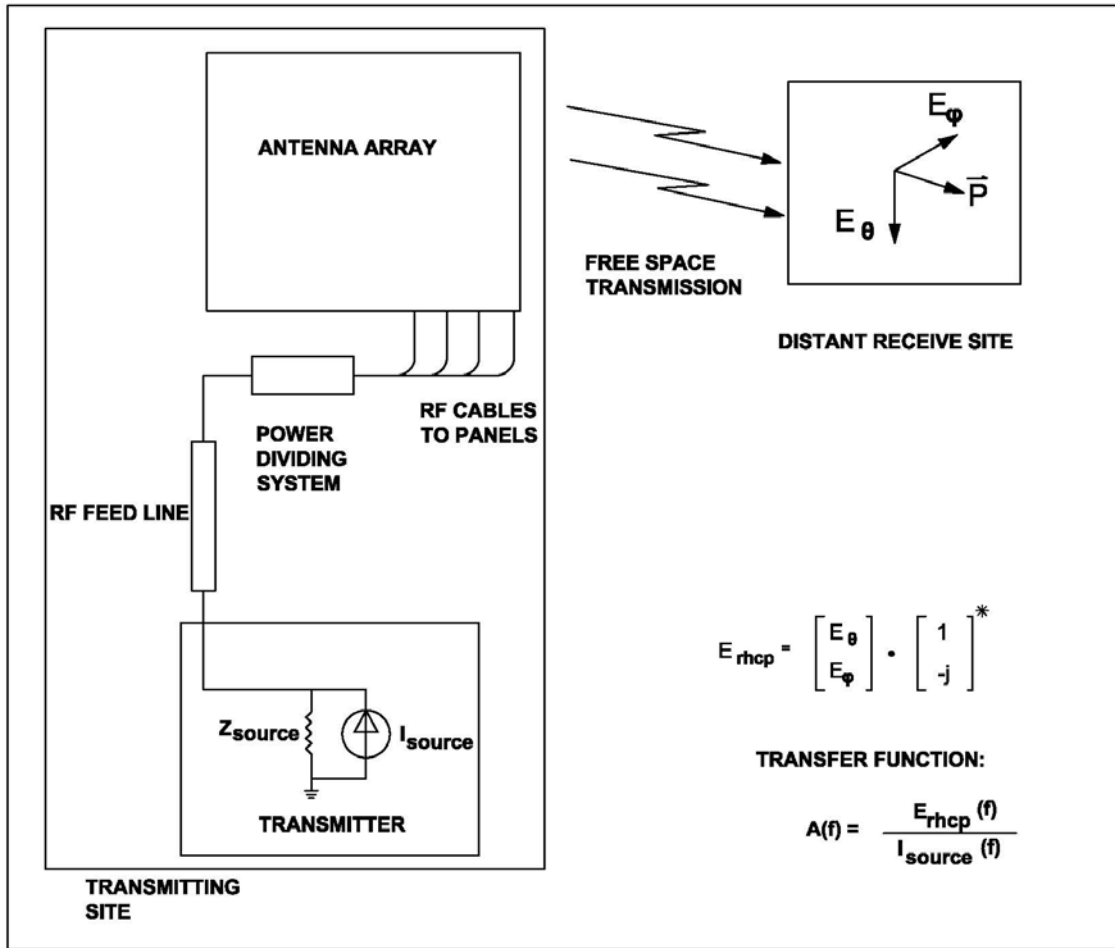


Figure 1

Antennas Studied: A broadband panel antenna array was used as the primary basis for this study. This system consists of 3 faces and four bays, for a total of 12 antenna panels. As each panel uses two vee dipoles, there are a total of 24 dipoles in this array.

In one configuration the panels are arrayed as shown in Figure 2 below and fed to give an omnidirectional pattern. An isometric view of this array is shown in Figure 3.

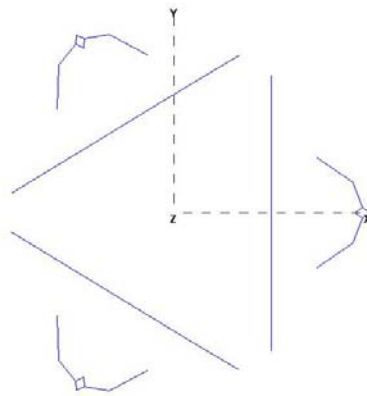


Figure 2

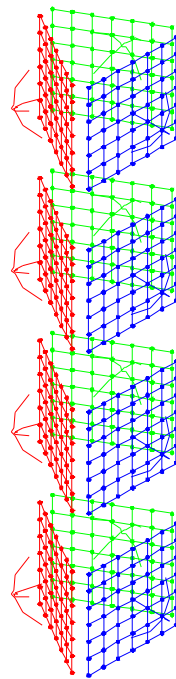


Figure 3

In the second configuration, the panels are arrayed as shown in Figure 4. Here, omni-directional performance was achieved by using lateral panel offset and a rotational phasing scheme (0, 120°, -120°).

A third configuration consisting of a single vertical dipole was analyzed. The same analysis was performed, but no power dividers or rf cables were used, other than the RF feed line.

Each antenna system was analyzed with variations in the following parameters: transmitter source impedance (50,  $\infty$  ohms) and feed line length (0, 500 feet), nominally, assuming a relative wave velocity of 1.0.

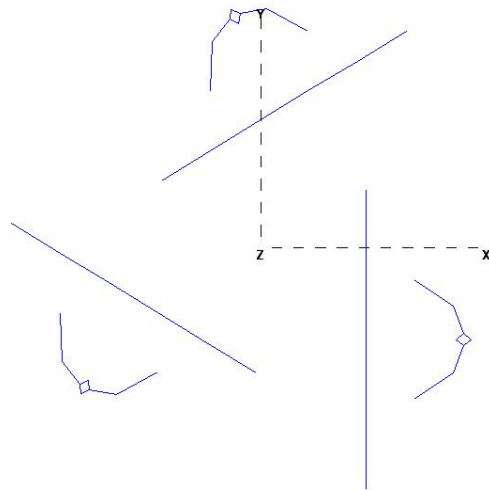


Figure 4

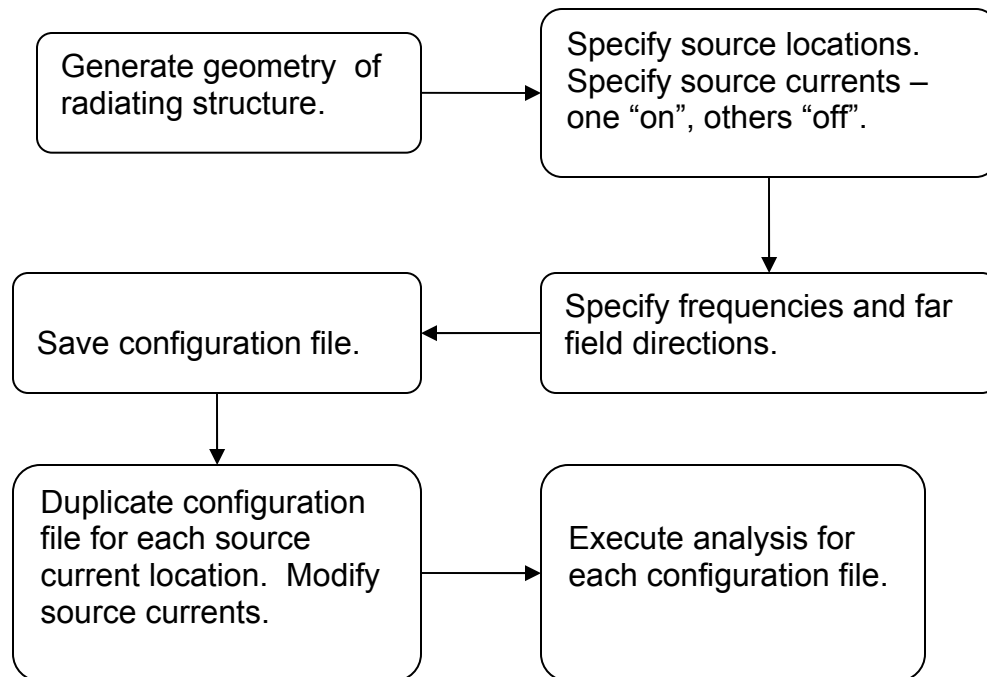
Lastly, the simple case of a resistor at the end of a transmission line is evaluated to demonstrate the effect of an unterminated line of substantial length.

Computation Method: A commercially available antenna analysis program<sup>2</sup> was utilized to make the electromagnetics calculations. The antenna structure was modeled as a series of thin wires and the solution was obtained using the method of moments. The model consisted of the reflector panels and the radiating elements. The model did not include the balun structure or the supporting tower or mounting components.

The flow chart below summarizes the steps used in performing the computations using the Mininec™ program. The process was complicated by the need to generate 24 different problem files, corresponding to the 24 dipoles. In each of these files, only one dipole was excited, with the other dipoles set to a vanishingly small excitation current.

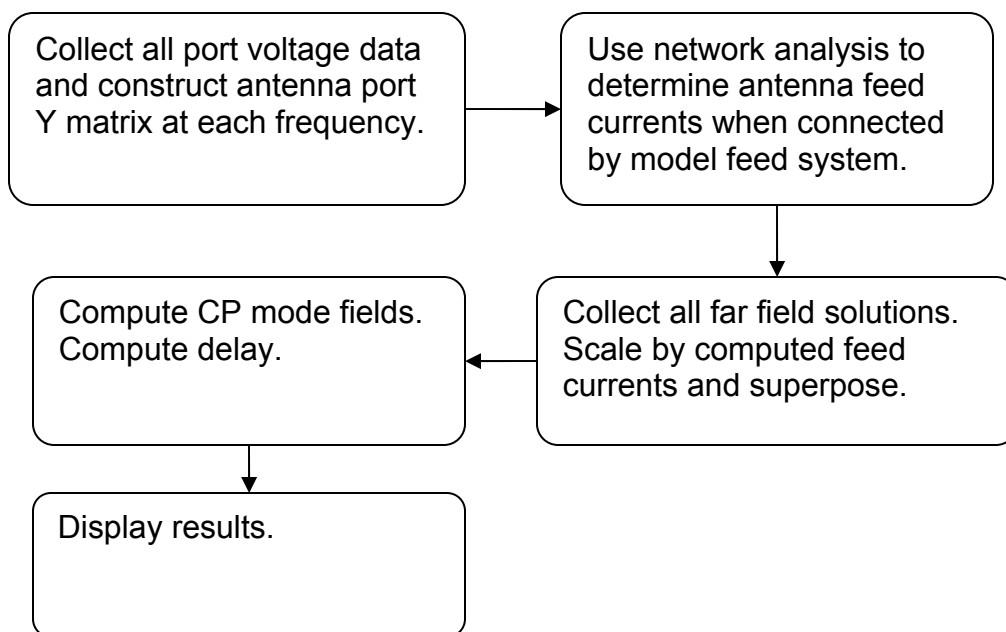
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<sup>2</sup> Expert Mininec Professional, V 9.0, EM Scientific



### Flow Chart for Mininec™ Computations

After the Mininec™ computations were complete, off-line processing was performed to obtain the results. In this case, Mathcad™ worksheets were written to process the data generated by the Mininec program. The flow chart below summarizes the off-line processing performed.

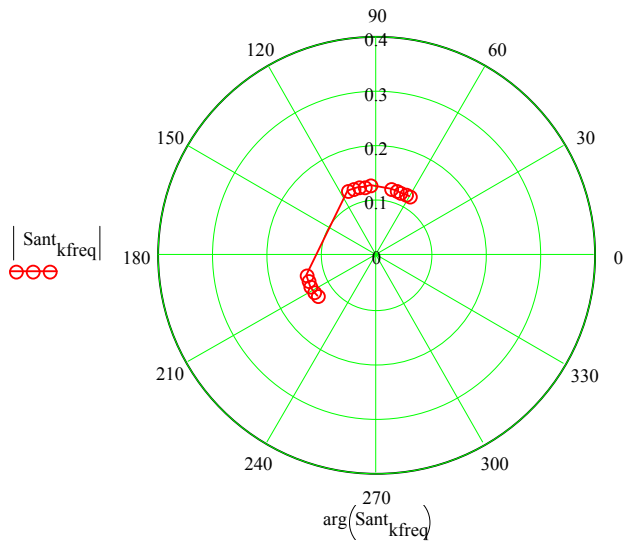


### FLOW CHART FOR OFF-LINE COMPUTATIONS

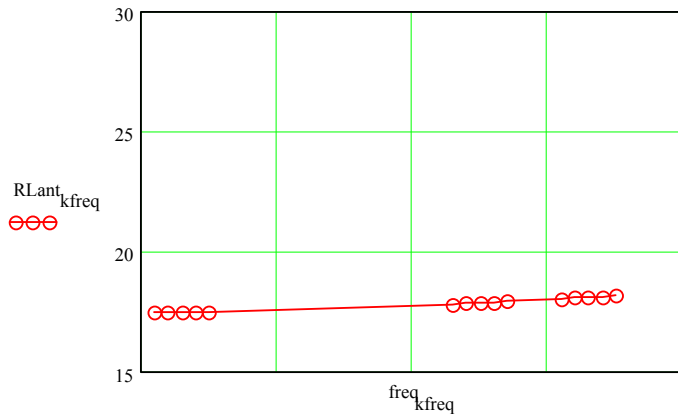
Of special interest is the computation of delay. Using the Mininec™ results, far-field phase data was computed at five discrete frequencies in intervals of 100 kHz across each 400 kHz FM channel considered. The delay  $\tau$  was computed by considering  $\tau = -d\phi/d\omega$ . In order to perform the differentiation, the discrete phase data was curve-fit to a 4<sup>th</sup> order polynomial. This analytical approximation for the phase function  $\phi(\omega)$  was then differentiated in a straight-forward manner.

Results, Configuration 1: The computations for Configuration 1 (Figure 2) are shown first. These were done for three FM channels covering a range of about 3.5 MHz. Figure 5 shows the antenna system input impedance characteristics. The return loss is about 18 dB across the three channels.





**Antenna Input Match,  
Γ Plane**



**Return Loss,  
Antenna Input**

Figure 5

The far field characteristics (RHCP mode) were computed for several values of transmitter source impedance and several values for the length of the RF feed line described in Figure 1. Figure 6 shows representative results for one of the FM channels at a single receive site (0 degrees azimuth). This data was computed assuming a transmitter source impedance of 50 ohms. (In this case the length of the RF feed line is immaterial.) The amplitude, phase and delay responses are shown. The amplitude is constant to within 0.05 dB, and the delay variation is limited to about 0.3 nanoseconds peak-to-peak. Note that the delay has been offset to give it 0 mean. This has been done throughout this work.

Transmitter = "50 Ohm Source"

Azimuth = 0 deg

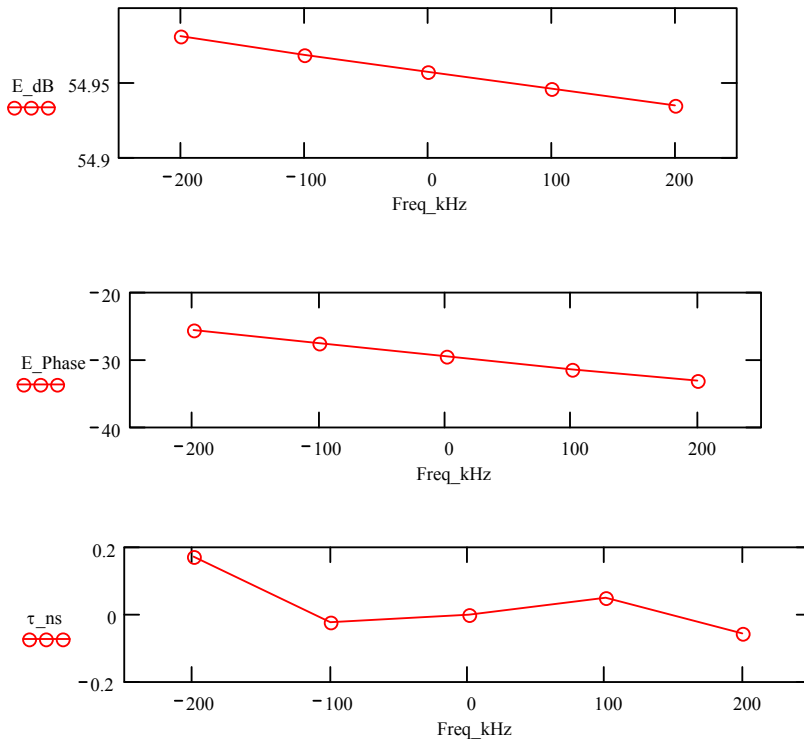


Figure 6

Figure 7 shows how this antenna behaves as a function of azimuth angle for the 3 channels considered. At each azimuth, the peak-to-peak amplitude variation was computed for each channel. Also, the peak-to-peak delay variation was computed. Each member of a family of curves represents the data for a particular channel. Also shown in Figure 7 is the azimuth pattern (RHCP mode) in the plane of the horizon for each channel.

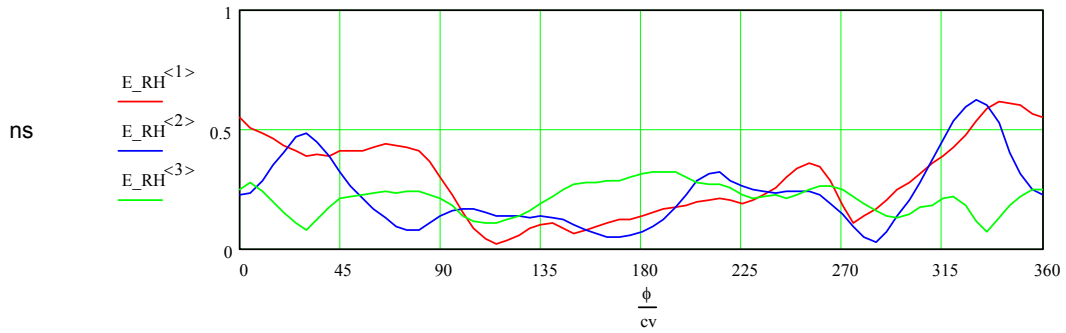
In no case did the peak-to-peak delay variation exceed 0.7 ns. The amplitude variations were limited to about 0.09 dB peak-to-peak.

**RIGHT HAND CIRCULAR Polarization**  
(co-pol)

SourceImpedance = 50

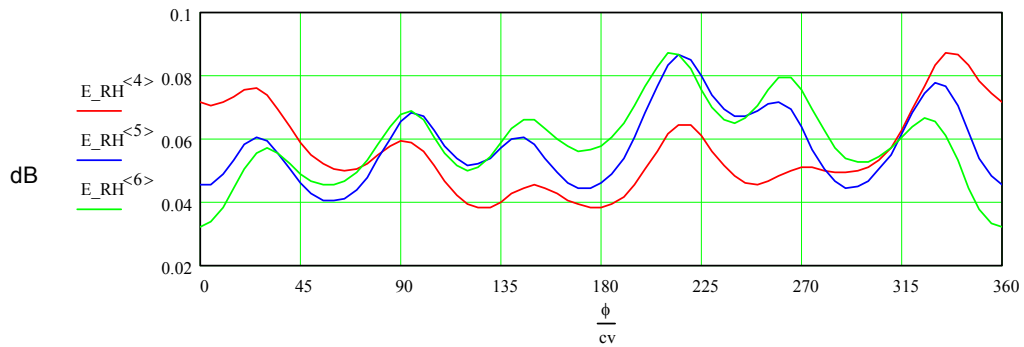
Peak-to-peak Delay Variation across 400 kHz Channel  
vs Azimuth

Channels 1, 2, & 3



Peak-to-peak Amplitude Variation across 400 kHz Channel  
vs Azimuth

Channels 1, 2, & 3



Azimuth Pattern,  
Linear Scale

Channels 1, 2, & 3

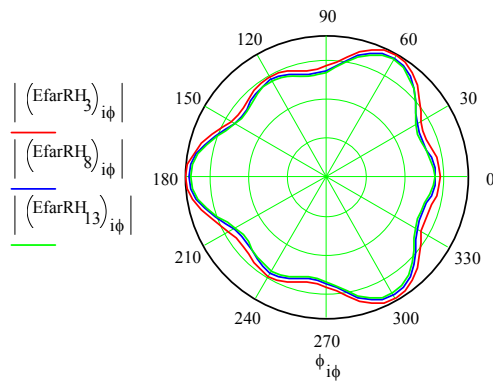


Figure 7

Now consider the results when a transmitter having high (or low) source impedance is used. The assumed value is 500 ohms. If the transmitter was placed immediately next to the antenna (or if the RF feed line was very short), the group delay variation would be limited to less than 5 ns and the amplitude variation would not exceed 0.25 dB. However, if a more typical line length of 500 feet is assumed, the results are drastically different. The worst case peak-to-peak delay and amplitude variations are 251 ns and 1.87 dB respectively. These results are shown in Figures 8 and 9.

Figure 8 shows the amplitude, phase and delay response across a specific channel at a specific receive site, as well as the load impedance seen by the transmitter.

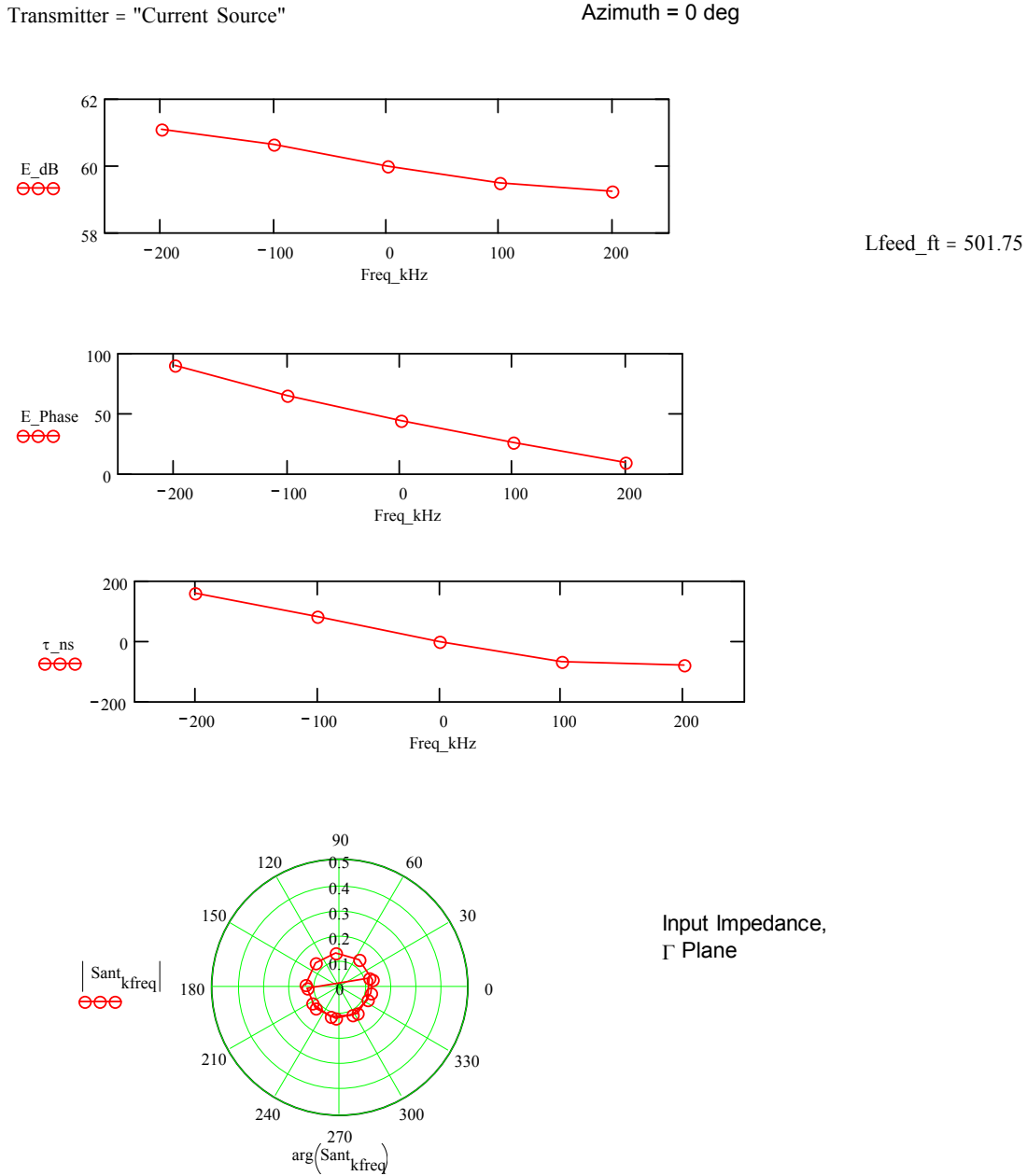


Figure 8



Here, the long transmission line delay causes the impedance to be stretched around the reflection coefficient plane, presenting the transmitter with a rapidly changing load impedance across the channel.

Figure 9 shows how the three channels behave at various azimuth angles.

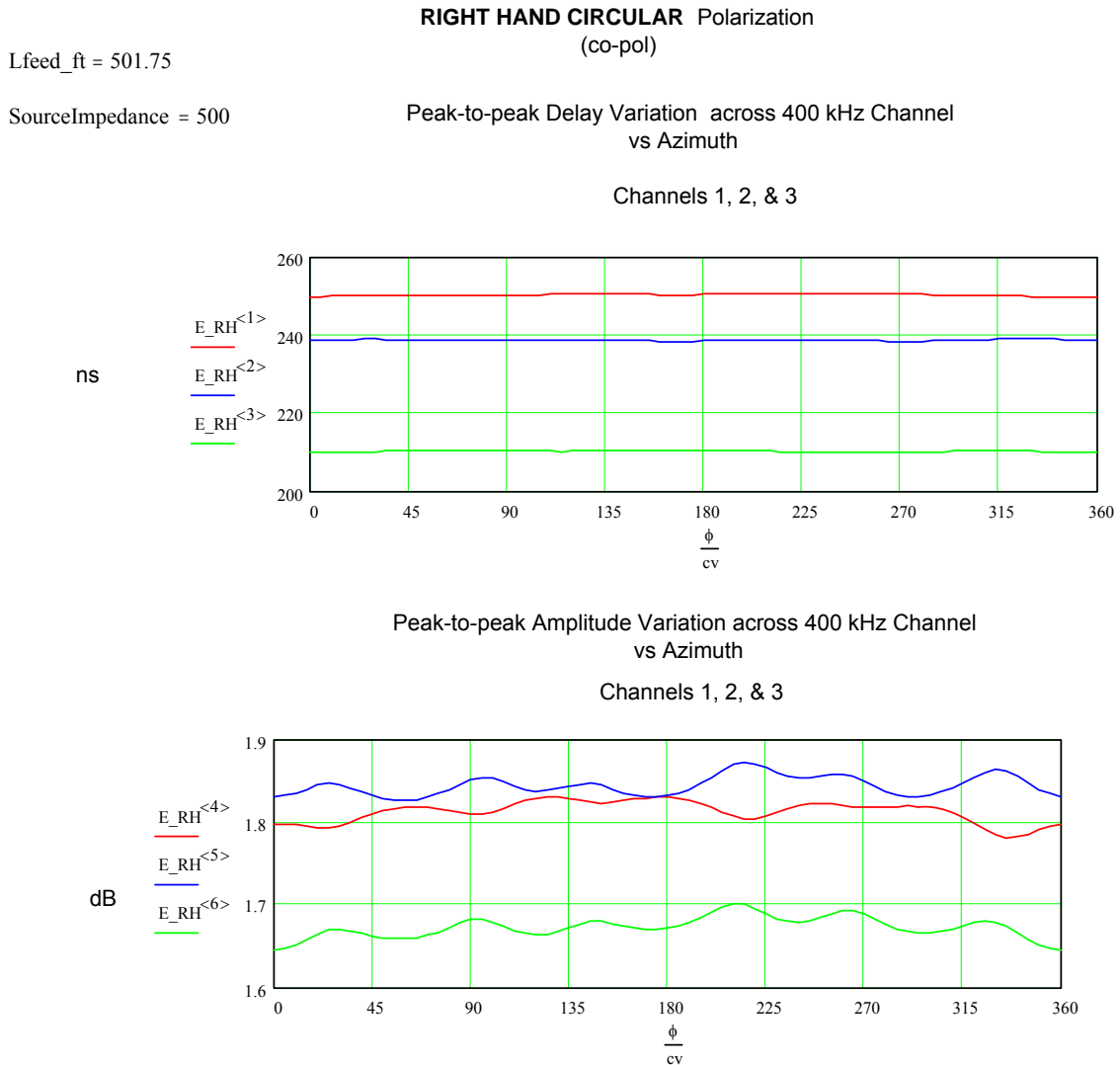
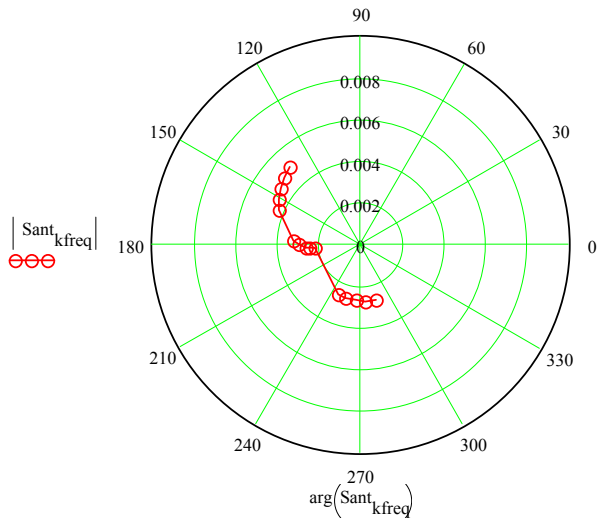


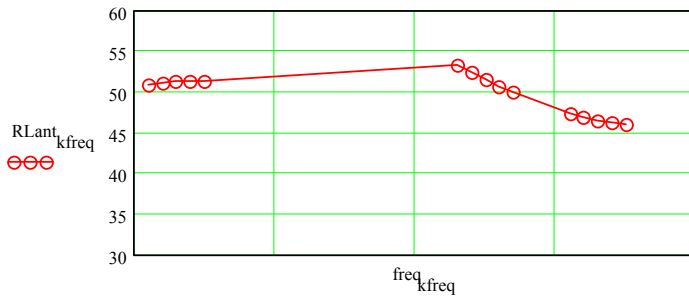
Figure 9



Results, Configuration 2: The computations for Configuration 2 are shown next. Recall that this antenna system (see Figure 3) uses a different arraying scheme and uses rotational phasing. This gives a better impedance match across all channels, as shown in Figure 10. We see that the return loss is better than 40 dB across the entire band of frequencies studied.



**Antenna Input Match,  $\Gamma$  Plane**



**Return Loss, Antenna Input**

Figure 10

Figure 11 shows the behavior across one of the channels of the RHCP mode far field at one receive location using a transmitter with an effective source impedance of 50 ohms. The amplitude variation is about 0.2 dB and the delay variation is about 2.2 ns.

Transmitter = "50 Ohm Source"

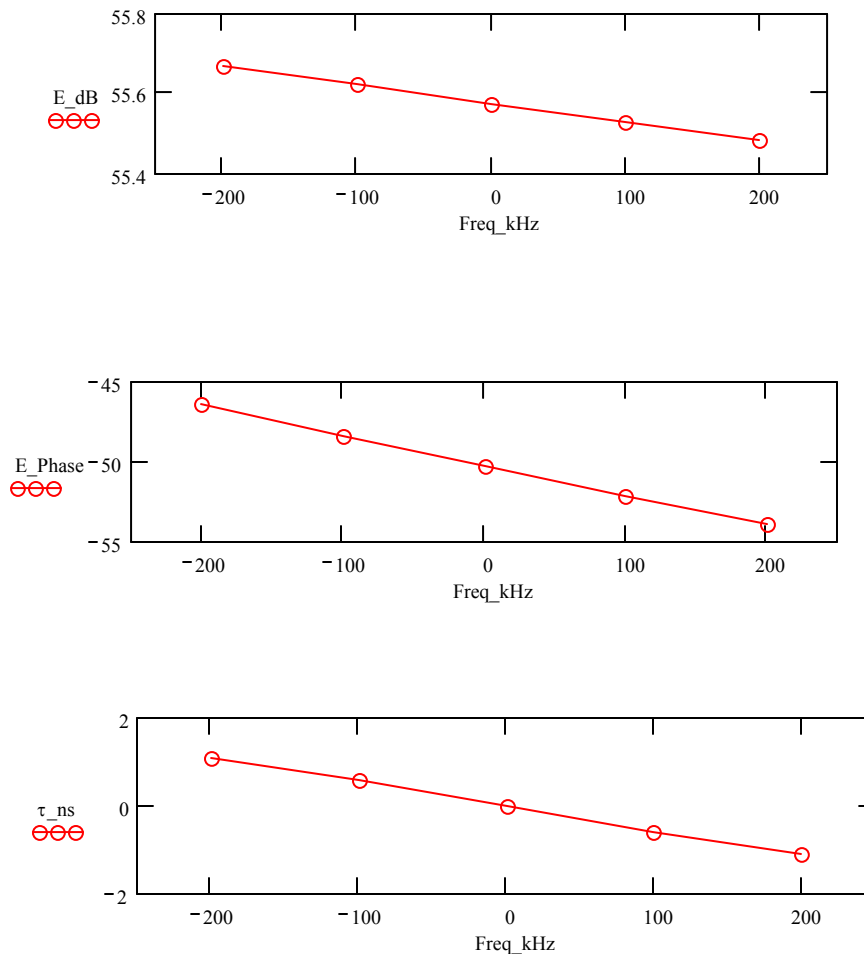


Figure 11

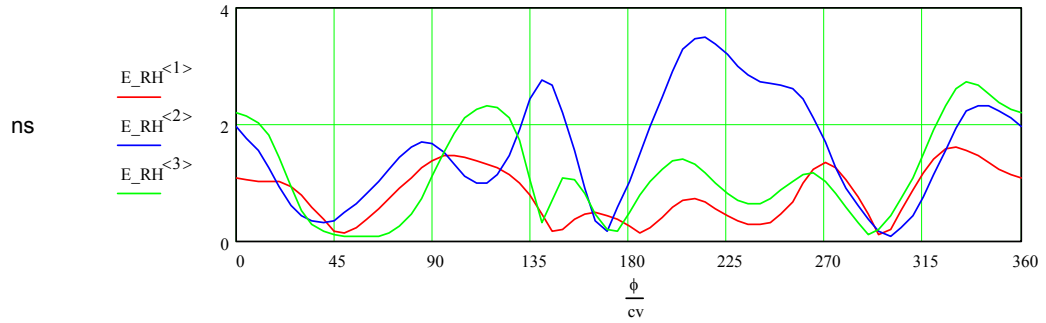
Figure 12 shows the behavior of this system at all azimuth angles for the three channels. The worst case peak-to-peak delay and amplitude variations are 3.49 ns and 0.25 dB respectively.

Transmitter = "50 Ohm Source"

**RIGHT HAND CIRCULAR Polarization**  
(co-pol)

Peak-to-peak Delay Variation across 400 kHz Channel  
vs Azimuth

Channels 1, 2, & 3



Peak-to-peak Amplitude Variation across 400 kHz Channel  
vs Azimuth

Channels 1, 2, & 3

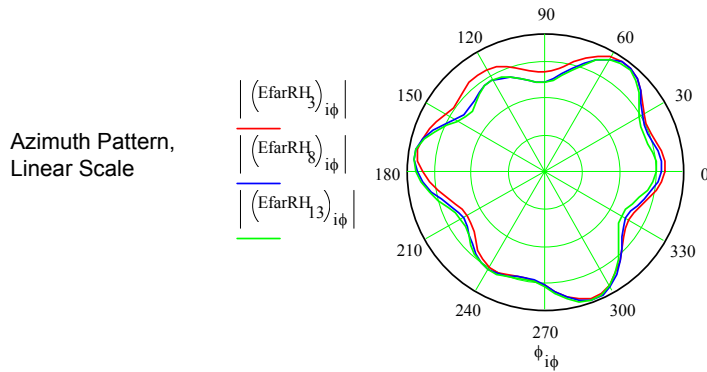
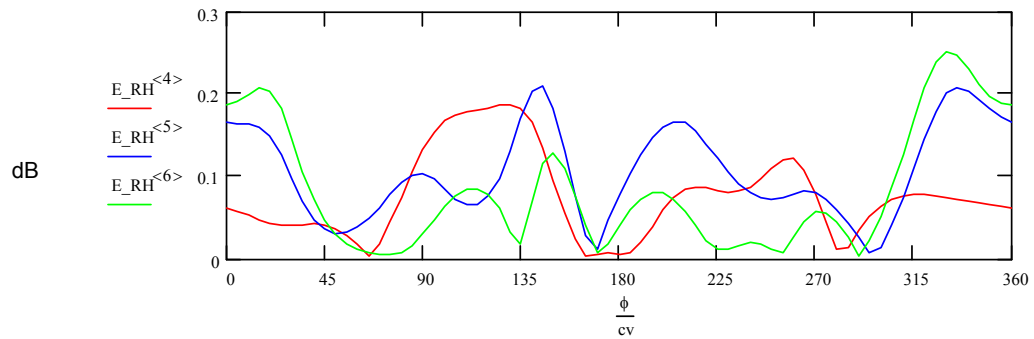
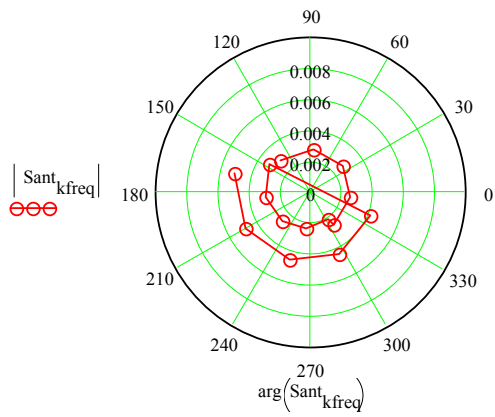


Figure 12

Figures 13, 14, and 15 show the results of using a 500 foot RF feed line and a transmitter which has a source impedance of 500 ohms. Figure 13 shows the load impedance presented to the transmitter. Even though it is stretched out by the feed line delay, the reflection level is so low that it is of little consequence.







Transmitter Load Impedance,  
 $\Gamma$  Plane

Figure 13

Transmitter = "Current Source"

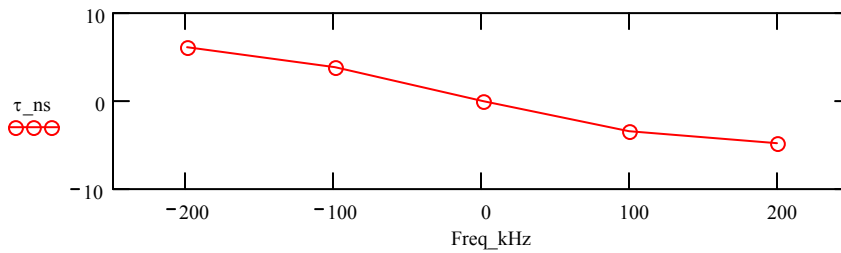
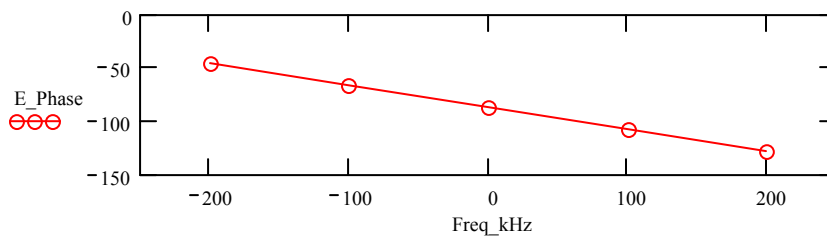
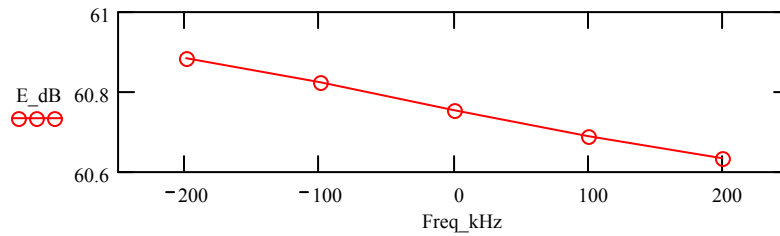


Figure 14

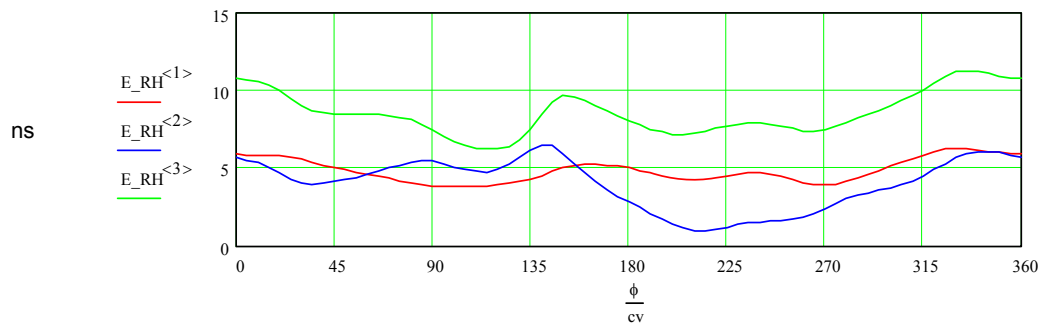
Figure 14 shows the behavior across one FM channel at one receive location. Figure 15 shows the far field behavior of all three channels at all azimuth angles. The worst case peak-to-peak delay and amplitude variations are 11.3 ns and 0.31 dB respectively.

Transmitter = "Current Source"

**RIGHT HAND CIRCULAR Polarization**  
(co-pol)

Peak-to-peak Delay Variation across 400 kHz Channel  
vs Azimuth

Channels 1, 2, & 3



Peak-to-peak Amplitude Variation across 400 kHz Channel  
vs Azimuth

Channels 1, 2, & 3

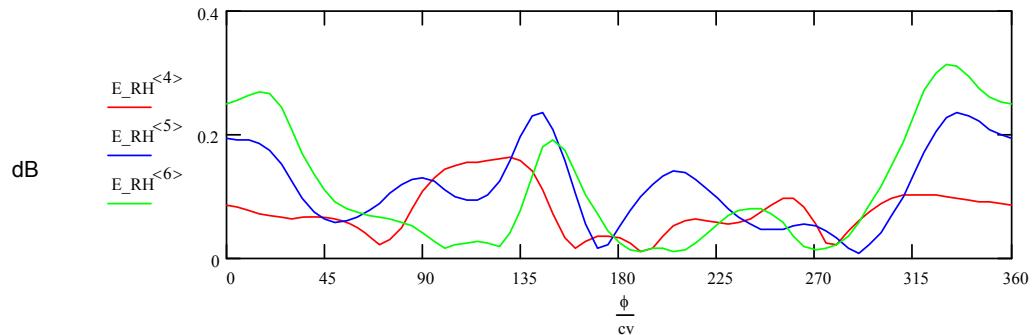


Figure 15

Results, Single Dipole: Similar computations were made for an antenna system consisting of a single dipole and a simple matching network. This analysis was carried out at 98 MHz. Table 1 below summarizes the results of those calculations.



### SINGLE DIPOLE

<u>Source Z</u>	<u>Δ GAIN</u>	<u>Δ DELAY</u>	<u>ANTENNA RETURN LOSS</u>
50	0.04 dB	0.01 ns	16.3 dB
∞	1.44 dB	81 ns	16.3 dB
∞	0.54 dB	32 ns	26.4 dB
∞	0.30 dB	19 ns	32.0 dB

Table 1

Here the RF feed line is 201 feet and the effective transmitter source impedance is either 50 ohms or infinite, a slight departure from the parameters used earlier. Note that antenna matching circuit at the antenna input was adjusted to give three different reflection levels: 16 dB, 26 dB and 32 dB return loss.

A matched source transmitter (Source Z = 50Ω) will provide very good far field gain and amplitude response even with an antenna having a 16 dB return loss.

A current source transmitter (Source Z = ∞ ) will again provide degraded far field response in the face of a mismatched antenna. With an antenna return loss of 26.4 dB (VSWR = 1.1:1) the in-channel gain variation is 0.54 dB and the delay variation is 32 ns.

Results, Resistively Mis-matched Transmission Line: For purposes of evaluating the significance of the impedance mismatch on a long transmission line, consider a simple system consisting of a current source transmitter, a long transmission line, and a load resistor whose resistance gives a reflection coefficient magnitude  $\rho = |\Gamma|$  relative to the characteristic impedance of the transmission line. The voltage across the resistor will be proportional to the phasor sum  $1 + \Gamma$ . If the line is sufficiently long (on the order of 600 feet for a 400 kHz channel), the phasor  $\Gamma$  will rotate in a full circle as the frequency is swept across the broadcast channel.

One can derive the maximum variation in the group delay for such a system to be

$$\Delta\tau = 4\rho(L/v) / (1-\rho^2) ,$$

where L is the length of the transmission line and v is the wave velocity in the transmission line.

The amplitude variation will be the VSWR or, in dB,  $20 \log [(1+\rho) / (1-\rho)]$ .

Assume that  $\rho$  is 1/8 (18 dB return loss). Then for 500 feet of transmission line the expected delay variation across a 0.4 MHz bandwidth due to the transmission line mismatch is 262 ns, and the amplitude variation is 2.18 dB, which is roughly the same as seen in the first example.

For a given value of  $\rho$  and a given maximum value for  $\Delta\tau$ , the length of transmission line allowed would be

$$L/v = \Delta\tau(1-\rho^2) / (4\rho) .$$

For a maximum allowable value of  $\Delta\tau = 600$  ns, and a value of  $\rho = 0.2$  (14 dB return loss, VSWR = 1.5:1), the maximum permissible line length for use with a current source transmitter would be 720 ns, or about 708 feet in a vacuum.



Discussion: Both matched impedance sources and high impedance sources were used in this analysis. Where the source impedance was assumed to be high (current source case), the same results could have been achieved by using a low source impedance (voltage source case), since adding  $0.25\lambda$  of transmission line to an RF current source will give a voltage source. As a point of clarification, the length of the RF feed line used was adjusted (within  $\pm 0.5 \lambda$ ) to give the worst case performance.

The effective source impedance of a transmitter will be determined by the transmitter architecture. A quadrature hybrid used to combine the outputs of the final rf power amplifiers *can* serve to provide a matched source impedance. Also, active equalization based on an accurate directional sample of the transmitter output wave may also yield this characteristic.

Conclusions: A summary of the computations reported above is shown in Table 2 below.

System	Return Loss	Source Impedance	Transmission Line Length (nom)	Variation, Amplitude(dB)	Variation, Delay (ns)
Array 1	18 dB	50	500'	0.09	0.7
Array 1	18 dB	500	500'	1.87	251
Array 2	40+ dB	50	500'	0.25	3.49
Array 2	40+ dB	500	500'	0.31	11.3
Single Dipole	16 dB	50	200'	0.04	0.01
Single Dipole	16 dB	inf.	200'	1.44	81
Resistor	14 dB	inf.	680'	3.52	600

Table 2

For the systems studied here, the contribution to the envelope non-linearity by the antenna system is primarily via the antenna input mismatch, the length of the RF feed line, and the effective source impedance of the transmitter for the systems described here. Systems using transmitters with source impedances matched to the characteristic impedance of the RF feed line show very good performance in all cases studied across a 400 kHz broadcast channel relative to the specification of 1.0 dB maximum gain variation and 600 ns delay variation.

In many cases, the delay variation performance may be kept within the 600 ns specification, but the amplitude variation can exceed the 1.0 dB peak to peak variation. See Table 2.

Systems using transmitters having an equivalent source impedance which has a high effective VSWR relative to the characteristic impedance of the RF feed line may not perform as well. In those cases low antenna input VSWR may need to be maintained in order to achieve similar envelope linearity performance against the specification.